

INTRODUCTORY HEAT-TRANSFER  
E.L.Widener - MET. Dept.  
Purdue Univ. - W. Lafayette, IN.

PREREQUISITE KNOWLEDGE: Typical high-school students of physics or chemistry should understand basic concepts of mechanics (force, work, momentum, energy, velocity, acceleration) in fundamental units (U.S. and S.I.) of basic dimensions (Length, Mass, Time).

OBJECTIVES: To introduce that notorious necessity, known as "thermo-dynamics", in existing heat-treating experiments using available items. To define thermal properties of materials: visualize expansivity, conductivity, heat-capacity, and melting-point of common metals; remember basic values: compare commercial materials, and consider electrical/mechanical analogs.

EQUIPMENT & SUPPLIES: Beakers (500 to 1000 ml) or buckets (2-5 gallon) for water-oil-sand quenches. Furnace, torch, or burner (electric or gas) for red-hot specimens; to re-heat specimens (tempering or aging). Grating (expanded-metal, wire-mesh) and firebrick (supports) for a cooling table. Piece of pipe (steel, plastic) about 10" long (25 cm) and 4"-Schedule 40 size (10 cm round); with circumferential holes (6-8) for 1/8" rods (wires) about 6" long (say 3 mm X 15 cm). Coffee-pot or hot-plate, to boil water. Stop-watch (or timer) and thermometers (dial or glass). Tongs, gloves, and safety glasses.

BACKGROUND:

In ancient Greece and Persia, heat was considered a universal element (earth, air, water, fire); but not until 1698 (Savery steam-pump) and 1712 (Newcomen steam-engine) was heat reified to mechanical work. [1] The materials lab is a good place to demonstrate the dynamic process of "heat transfer", to elucidate the elusive concept of "heat", and to inter-relate "heat/work/energy".

Rooted in Old English words (hot, hetup), heat is a fundamental and fascinating subject, variously defined: energy added to substances to raise temperature, change-state, or accelerate reactions; energy associated with random motion of atoms/ions/molecules; energy flow from high temperature to low. Although heat is not temperature nor a property of materials, it is prominent in properties and processes which are temperature-related: expansivity ( $\alpha$ ), density ( $\gamma$ ), conductivity ( $\sigma, \kappa$ ), heat capacity ( $C_p$ ) viscosity ( $\mu$ ), melting point ( $t$ ); and annealing, normalizing, quenching, tempering, stress-relieving, aging, warping, corroding, hysteresis, friction.

DEFINITIONS:

Heat ( $Q$ ) is thermal-energy in transit (area under a T-S curve, a plot of temperature vs. entropy) because of a temperature difference. Similarly, Work is mechanical-energy in transit (area under a P-V diagram, a plot of pressure vs. volume) because of a force difference. Also, Amperage is electrical-energy in transit, because of a voltage (potential difference).

Heat has a work-equivalent (about 778 ft-lb/Btu) but neither of these "path functions" are identical to Energy, a "point function." Think of a truckload of goods, partway between a warehouse and a shop; heat is like the shipment, but energy is like an inventory (at warehouse or shop)[2]. Similarly, an accountant takes the difference between "balance sheets" (field strengths) as "profit-or-loss" (heat transfer, work done).

Heat is generally measured in units of joule, calorie, or Btu. Work or energy is expressed in foot x pounds (ft-lb) or joules (newton-metre). The U.S.A. still prefers to use the "British Thermal Unit" (Btu), defined as the energy to raise a pound (Avoirdupois) of water (atmospheric pressure) by a Fahrenheit degree (F°), or absolute Rankine degree (R°). Think of this as the chemical energy (potential) in a regular, wooden, kitchen-match (about 3" long). It is almost a kilo-joule.

The old metric calorie was defined as the energy to raise a gram (ml) of water (atmospheric pressure) by a Centigrade degree (C°, now called Celsius) or absolute Kelvin degree (K). Note this standard for S.I. (Système Internationale) disallows a degree mark (K°), which precludes the convention of Jakob/Hawkins[3]: Water freezes at 32°F, but boils 180 F° higher, a useful distinction between "point" and "line" functions. Also note the dieticians' usage of "Calorie", which is a "kilo-calorie" of food (1,000-cal = Cal).

The S.I. unit of work, heat, and energy is the joule; i.e., force (newton) times distance (metre). Of course, the newton is the mass (kilogram) times acceleration (metre per second-squared). Note "force" is better defined as "time rate-of-change of momentum"; so,  $F = d(mv)/dT$ . Since 2.2 lb (mass) is about 1-Kilogram, and 2.54 cm is exactly 1-inch, the kilo-joule is about a Btu. A newton is about a quarter-pounder.

More precisely, a Btu = 1.055 kJ = 778.16 ft-lb = 251.98 small cal. A calorie = 4.1868 J. A kilogram = 2.205 lb (Av). A lb = 4.448 N. And a Watt = J/s = 3,413 Btu/hr.[4]

Generally, hydraulic analogs are more graphic than thermal systems. Mechanical to thermal conversion is more efficient (up to 100%, including friction) than thermal to mechanical. An electrical system is more easily and accurately measured than its thermal analog.

Thus, electrical capacity ( $C^+$ ) is charge (coulombs) per voltage difference ( $C^+ = Q^+/\Delta E$ ); and thermal capacity (C) is heat input ÷ temperature difference ( $C = Q/\Delta T$ ). Sometimes this is mis-named "heat-content." Specific heat-capacity is then standardized at constant pressure ( $C_p = Q/m \times \Delta T$ ) per unit mass. So,  $C_p = \Delta h/\Delta T$  in terms of Enthalpy ( $\Delta h = Q/m$ ).

Hydraulic flow rate (Q) is cross-sectional area (pipe) times average-velocity (fluid), so  $Q = AV$ . Then, "pipe conductivity" could be expressed as  $C = QL/L^2 \times \Delta T \times \Delta t$ , the analog of thermal conductivity.

Electrical conductivity ( $\sigma$ ) is the inverse of resistivity. Use Ohm's Law ( $E = IR = \text{Ampere} \times \text{Ohm}$ ) and define an Ampere (Coulomb/second); then  $\sigma = 1/RL$ .

Thermal conductivity ( $\kappa$ ) is heat input X length ÷ (area X time interval X temperature difference). Thus,  $\kappa = QL/L^2 \times \Delta T \times \Delta t$ .

The classic Dulong-Petit Rule (1819) says: Specific-heat ( $C_p$ ) times Atomic-weight (amu) is approximately constant (6.4) for solid

elements (above 40 wt.). The classic Wiedemann-Franz Ratio says: Thermal-conductivity ( $\kappa$ ) over Electrical-conductivity ( $\sigma$ ) is approximately constant ( $7.5 \times 10^6, J \times \Omega / s \times K$ ) for metals at constant temperature. This constant is also the "Lorenz" constant ( $L$ ) times absolute "Kelvin" degrees ( $t$ ) for variable-temperature tests.

EXPERIMENTS: Now the fun begins!

### 1. Relative Quench Factor (RQF)

A steel disk (AISI 1040, 2" dia. X  $\frac{1}{4}$ " thick) is heated red-hot ( $1650^\circ F$ ,  $900^\circ C$ ) and quenched quickly in a pail of water ( $70^\circ F$ ,  $21^\circ C$ ). The sizzling will stop in about 30 seconds, so the disk is not too hot to touch. A second disk (AISI 1080) quenched in water will take about 30 seconds, but has twice the carbon (0.80 W/O) and twice the BCT martensite grains (Body Centered Tetragon) so the disk cracks badly. A third disk (AISI 1080) quenched in oil will take about 90 seconds, make less martensite (shown by Rockwell C hardness), but has no cracks. Thus, the oil is a slower, safer quench; higher boiling point and greater viscosity are the reasons. Show students how a sore thumb, soaked in hot-water, becomes comfortable unless "stirring" ensues; thus, heat-transfer is enhanced by "turbulence", to reduce the laminar boundary-layer in water.

An aluminum disk (AA 6061,  $1\frac{1}{4}$ " dia. X 1" thick) is heated red-hot ( $1650^\circ F$ ); it melts to a "pancake" in the furnace, exhibiting a black alumina coating typical of "emery paper" (used for metallography grinding). A second Al disk is "solutionized" ( $990^\circ F$ ,  $532^\circ C$ ) and quenched quickly in the pail of water ( $70^\circ F$ ). We can predict how long it takes to stop sizzling, so the disk is not too hot to hold (threshold of pain is  $140^\circ F$ ,  $60^\circ C$ ). Use  $RQF = Q \text{ of Al} \div Q \text{ of steel}$ , where  $Q = C_p \times \gamma \times t$ ; i.e.,  $(Btu/lb/F^\circ) \times (lb/ft^3) \times (ft^3) \times (F^\circ) = Btu$ .

$$\text{Thus, } RQF = \frac{(0.215) (170 \times 1.77) (990 - 70)}{(0.110) (480 \times 1.57) (1650 - 70)} = \frac{2}{1} \times \frac{1}{3} \times \frac{1}{1} \times \frac{2}{3} = \frac{4}{9}$$

Assume a constant  $70^\circ F$  in a 5-gal water pail. Note how volumes of disks ( $\gamma$ ) in cubic inches will cancel, so conversion to cu ft is not needed.

It will take the Al disk about  $\frac{4}{9} \times 30 \text{ sec} = \boxed{13 \text{ sec}}$  to cool.

### 2. Furnace Calibration Test (FCT)

Assume the heat-treating shop wants to check the furnace controls (temperature control, thermocouple, and readout) every shift. The "suggestion - box" brings a test proposal for \$100 award: Drop 10-disks of red-hot steel in 1-gallon water bucket and measure the temperature-rise, with stainless-dial thermometer. The foreman fears a steam explosion. Do we O.K. the test? Assume a heat-balance and neglect losses.

Say  $Q$  out of steel =  $Q$  into water; where  $Q = C_p \times \gamma \times \Delta t$ : the  $Q$  is "absolute value" of heat; and  $t$  is final temperature of ten-cold disks or a warm gallon (8.33 lb). Therefore,

$$0.11 (10 \times 480 \times 1.57/1,728) (1,650 - t) = 1.0 (8.33) (t - 70)$$

$$\text{So, } 0.4797 (1650 - t) = 8.33 (t - 70) \text{ So,}$$

$$791.5 - 0.48 t = 8.33 t - 583.1$$

$$7.85 t = 1374.6, \text{ and } \boxed{t = 175^\circ F}$$

We conclude the water won't boil, the test is simple and safe, and

the \$100 award is well deserved. Of course, the men have already run the test, a disk at a time, and know it is O.K. An elegant thermodynamics equation says  $Q_{in} = -Q_{out}$ , with temperature differences expressed as "final-original." Ours were "hot-cold".

### 3. Specific Heat Capacity (water)

Worldly wisdom says, "a pint's a pound the world around", if it's water. Milk is mostly water. So, take a pint of milk and heat its bottom with a kitchen match (one-Btu). With no heat losses, the milk only heats one  $F^{\circ}$ , a visual proof for  $C_p$  of  $H_2O$  (one Btu per pound per  $F^{\circ}$ ). No wonder water is used to quench red-hot steel and to douse fires.

Next, visualize a Btu as 778 ft-lb. An 80-lb bag of "softener salt", carried up 10-steps (1 foot risers) to the mezzanine, can injure a worker on the ground floor (800 ft-lb is bad). An 80-lb cannon-ball, dropped on your foot (10 ft below) is worse. Holding your hand over a wooden match (one-Btu) gives "roast hand", but not "roast milk". This is real energy!

### 4. Specific Heat Capacity (metals)

Get samples of 5-common alloys (copper, aluminum, yellow-brass, plain-steel, and stainless-steel). All samples must have the same weight (say 5 ounces); it's good to have the same surface area (a challenge) but not essential. Take 5-beakers; add ice-water enough to cover any sample (aluminum has most volume); but each beaker must have the same volume of water.

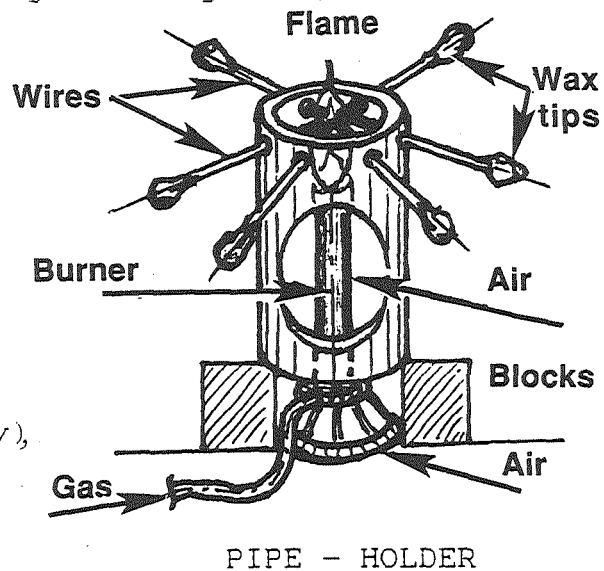
Meanwhile, the metal samples are immersed in a pan of water and brought to a boil. Put a thermometer in each beaker; stir and measure the "ice-water" temperature; a rugged dial-thermometer is good. Then, add a hot sample to each beaker, stir to avoid stratification, and read the maximum temperature rise ( $\Delta t$ ). Compare with values of  $C_p$  and  $\gamma$  from a handbook, which should vary directly with  $\Delta t$  - values, but inversely with density. Aluminum is lightest, so  $C_p$  is largest (about 0.215 Btu/lb/ $F^{\circ}$ ). Steel and Copper have less  $C_p$  (about 0.11).

### 5. Thermal Conductivity (metals)

Get wire samples (say 1/8" dia. X 6" long) of common metal alloys (copper, aluminum, brass, steel, stainless) and insert them in your "pipe holder" (4" - Sched. 40 X 10" long), having radial holes and air-passages (see Sketch):

Each wire, with a ball-of-wax on the outer end, looks like a "Q-tip". Inner ends of wires meet at the pipe-center, like spokes in a wheel. A burner-flame heats the wires simultaneously (at the hub).

The wax falls off the copper, then aluminum - brass - and steel; the stainless steel stays cold. Measure the drop-off times by stop-watch; compared with handbook values for  $\kappa$  (thermal conductivity), these metals should differ by halves: copper 1, aluminum 1/2, brass 1/4, steel 1/8, stainless 1/16. No wonder



aluminum and stainless-steel are hard to weld. Compared to plain-steel, aluminum conducts too fast, holds heat too long, and tends to melt too much; stainless is slow to preheat, hard to preheat evenly, and tends to warp.

Notice the "oxide" colors (ranging from yellow to blue) which correspond to temperature (430 - 640° F). Do not confuse with "hot-metal" colors; hot-rolling is "red-hot" at 1650° F; cold-rolling is "black-hot" below 1333° F (allotropic transformation, from FCC austenite to BCC ferrite).

Throw in a "ringer" (copper-coated stainless welding-rod) and mystify the class, as the waxy tip stays cold indefinitely.

## 6. Melting Points (Solder)

Molded balls of solder (60-40 eutectic mix) and component metals (lead, tin) are made as "fish-line" weights (with a slot). An aluminum plate (say 4" dia) is dented with a ball-hammer (3-dents, in a triangular pattern). Placed on a ring-stand and heated by gas-burner, the balls will melt, but the aluminum plate should not. First, the solder ball collapses to a pancake; next, the tin ball; finally, the lead ball. Shut off the flame, tap the plate, and watch the shimmering "puddles" as they re-freeze. First is the lead; next the tin; finally the solder.

Discuss the "eutectic-solder" (for electrical joints) which freezes at a definite, lowest temperature); compare with "wiping solder" (for plumbing joints) which freezes over a range of temperatures (like slush). This illustrates the 2-phase mixture of liquid and solid solutions, seen on a "binary phase-chart" of Pb and Sn.

## 7. Expansivity (linear)

A stainless coffee-pot, fitted with a plastic-lid, may have easy clearance (cold) but becomes difficult to remove (boiling hot). Compare values of linear expansivity ( $\alpha_l$ ) for steel (0.000006/F°) and plastics (0.00006). Visualize expansion of a steel pipe as 6" per million" (16 miles).

Samples of Al rod ( $\alpha_l = 0.000009$ ) easily show expansion and contraction, if heated in boiling water (about 140 F° above 70° room temperature) and cooled on dry-ice (about 140° F below 70° F). Measuring can be done by a "vernier caliper" (to 0.001", called 1-mil) or a "micrometer" (to 0.0001"). Be careful of ice-crystals on a cold rod, interfering with measurements. Use a machinist's caliper (with center-screw adjustment) like an ice-man's tongs (a "go/no go" gage).

Note area expansivity ( $\alpha_A$ ) is about 2 X  $\alpha_l$  (210%); volume expansivity ( $\alpha_v$ ) is about 3 X  $\alpha_l$  (331%). When units are cancelled in a handbook ( $\text{in}^2 / \text{in}^2$ , or  $\text{in}^3 / \text{in}^3$ ) we generally assume published values are linear. When in doubt, find out! Remember, expansivity is generally measured close to room temperature. For red-hot steel, 6 "per million" is too little.

## CONCLUSION:

The materials lab experiments and demonstrations can introduce students to thermal properties, as well as mechanical. The shock of "thermodynamics" is alleviated, and electrical correlations with thermal properties are enhanced.

KEY WORDS: heat. work. energy. enthalpy: expansion. contraction:  
conduction. resistance; heat-capacity. heat-transfer.

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BIOGRAPHY:

EDWARD L. WIDENER

Teaches mechanical engineering technology at Purdue University (since 1978), concentrating on statics, fluid mechanics, materials, labs and technical writing...Member ASME, ASEE, ASM, TAPPI. Registered P.E. in New York and Indiana...ABET visitor in 1983-88...B.S. M.E. from Purdue University and M.S. E.M. from the University of Kansas...Taught evenings at IUPU-Indianapolis and at Danville, IL. Worked as Mechanical Development Engineer for "Coria" collagen casing with Teepak Co., Continental Group (1976-78). Process Group Leader for mechanical contractor, Baker-McHenry-Welch, Indianapolis, IN (1974-76). Project Leader for creped-wadding and secondary-fibers with Kimberly Clark Co., Memphis, TN (1968-74). Process Engineer for "Nomex" nylon with E.I. DuPont Co., Richmond, VA (1963-68). Associate Engineer for electro-furnace alloys with Union Carbide Co., Niagara Falls, NY (1952-60). Fuel Engineer with U.S. Steel Co., Gary, IN (1951-52).